The Predominating Influence of Moisture and Electrolytic Material Upon Textiles as Insulators [1]

By R. R. WILLIAMS and E. J. MURPHY

The insulating qualities of textiles vary with the amount of moisture present in them from hour to hour and are also strongly influenced by the amount of electrolytic material (salts, etc.) which the textiles contain. Electrolytic material may be washed out producing a commercially realizable increase in insulation resistance of the order of 50 times the original value.

The resistance of the animal fibers, silk and wool, is far greater for a given moisture content than that of cotton or of cellulose acetate, a derivative of cotton. It appears probable that the distribution of water as well as the quantity is important and that the two classes of fibers are characterized by different space patterns according to which the water is distributed. It is suggested that the space distribution patterns are associated with the colloidal structures of the materials and in turn with their chemical classification as proteins and celluloses respectively. Cellulose acetate absorbs little water as compared with cotton and is correspondingly superior electrically. However its resistance varies with moisture content in the same way as that of cotton.

A GREAT diversity of materials is used for insulating purposes. No simple descriptive term includes them all as the term "metals" includes commercial conducting materials. Yet in spite of this diversity it is to a great extent the quantity and mode of distribution of water in all insulators that determines their relative excellence. Were it not for the accumulation of moisture in it or on it the cheapest and mechanically most convenient material could, with rare exceptions, be used for the most exacting service.

At first glance it might seem possible to select insulating materials very simply according to moisture content, but a few illustrations will serve to show that wide contrasts exist in the response of insulations to a given amount of moisture. At one extreme is gutta percha, the classical insulation of submarine cables. If dry at the outset, it very gradually absorbs one or two per cent of moisture from the sea, but undergoes only a slight change in electrical characteristics in the process. Thereafter its water content and electrical properties are extremely stable in use. Rubber insulations used in air partake of these properties to some degree. Fluctuations in their electrical behavior never are large or sudden so long as they are mechanically intact. At the opposite extreme are the textile insulations which, especially if unimpregnated, are subject to every whim of the weather. Their water contents rise suddenly with corresponding changes in the relative humidity of the atmosphere, and the dielectric qualities

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faithfully reflect the moisture supplied from the air. A one or two per cent increment of moisture affects gutta percha scarcely at all but an equal amount has a most profound effect on the textiles.

The phenolized fibers, the impregnated papers, the cellulose esters, insulating varnishes and enamels, as well as glass and porcelain, are intermediate between the "waterproof" insulations and the textiles in their sensitivity to atmospheric moisture. We refer to these insulations, of course, in the forms in which they are ordinarily used, for brevity neglecting distinctions which might properly be made as to relative importance of surface and volume characteristics in the several cases.

Diverse as are the insulators in use, they have another common property of importance. They often contain, or have deposited on their surfaces, electrolytic material which dissolves in the absorbed water to form conducting solutions which are injurious to the insulating qualities of the material. This fact seems to be second in importance only to the prevalence of water in insulating materials. These electrolytic substances may be present as part of the natural constituents of the insulating material or as accidental contaminants; they may consist of the saline or organic constituents of the vegetable tissues which furnished the raw material, of by-products of the processes of manufacture, of degradation products of the insulating substances resulting from atmospheric oxidation or hydrolysis, or of atmospheric dust. Illustrative of the diversity of electrolytic material in commercial insulating materials are the natural ash constituents of textiles, pulp woods and other materials of vegetable origin; saline diluents of dyes used in fibrous materials; the quebrachitol of the latex of the rubber tree; acid resins produced by the atmospheric oxidation of rubber and gutta percha; and the free phenol present in phenol condensation products.

While the importance of moisture and of electrolytic contaminants in practical insulations has long had some recognition by electrical engineering opinion, especially in the telephone field, the foregoing general philosophy has been emphasized in the minds of the authors and their associates by the results of extended experimental studies of submarine insulation [2] and of textiles.[3]

[2] Williams, R. R. and Kemp, A. R., *Jour. Frank. Inst.*, 35 (1927). Lowry, H. H. and Kohman, G. T., *Jour. Phys. Chem. 31*, 23 (1927).

[3] *a.* Murphy, E. J. and Walker, A. C., "Electrical Conduction in Textiles. I. Dependence of the Resistivity of Cotton, Silk, and Wool upon Relative Humidity and Moisture Content," *Jour. Phys. Chem. 32*, 1761 (1928).

b. Murphy, E. J., "Electrical Conduction in Textiles. II. Alternating Current Conduction in Cotton and Silk," *Jour. Phys. Chem. 33*, 200 (1929).

c. Murphy, E. J., "Electrical Conduction in Textiles. III. Anomalous Properties of Conduction in Textiles," *Jour. Phys. Chem. 33* (1929).

Important contributions to the knowledge of the quantitative relations between the electrical properties of insulating materials and the moisture which they take up from the air have been made by Evershed,[4] Curtis,[5] Kujirai and Akahari,[6] Setoh and collaborators,[7] and other investigators. But in no published work, so far as we are aware, have data been given showing the quantitative relationships between the electrical properties of textile insulations and the electrolytic material which they contain. Data of this kind were obtained in the investigation of textiles mentioned above. Part of these data have been reported elsewhere,[3] but the investigation is being continued and a further report will be made when it is completed. It will require much further work to establish in detail the importance of contamination with aqueous solutions of electrolytes for every commercial insulating material. However, the presentation of the main thesis as a general one is abundantly justified by our constantly growing experience with cases in which such contamination of a variety of insulating materials has actually been found responsible for poor insulating qualities and for corrosion of metallic conducting or supporting elements in contact with them in electrical systems. This paper is intended to emphasize the importance of moisture and electrolytic material on the behavior of textiles as insulators and to discuss briefly the relation of electrical characteristics to physical structure and chemical constitution, so far as possible with the available facts.

General Characteristics of Textiles

It is obvious that the rapidity of response of textiles to atmospheric moisture is due first of all to their fibrousness which permits ready access to the interior of the mass through the large surfaces exposed. By contrast, the relative stability of rubber insulations, for example, is clearly due in part to the smaller ratio of surface to volume.

Since textiles are composed of fibers, it might seem that the resistance of a thread or the serving on a wire should depend largely on the resistances of the contacts between fibers. Further, the fibers themselves have superficial irregularities which would suggest that their resistance might vary widely from fiber to fiber of the same material. Table I*A* shows that single fibers of cotton and silk have a resistance [8]

[8] The experimental procedure is described elsewhere.[3a]

[4] Evershed, *Inst. of Elec. Eng. Jl.* (London) *52*, pp. 51–83, 1914.
[5] Curtis, Bur. of Standards, *Sci. Paper No. 234* (1915).
[6] Kujirai and Akahari, *Sci. Papers, Inst. Phys. & Chem. Res.* (Tokyo), *1*, pp. 94–124, 1923.
[7] Setoh and Toriyama, *Sci. Papers Inst. Phys. & Chem. Res.* (Tokyo), *3*, pp. 285–323, 1926.

TABLE I*A*

RESISTANCE OF COTTON AND SILK FIBERS

R is the resistance in megohms of a single fiber ½ in. long. Time allowed for equilibrium, 20 hrs. or more. Room temperature

Humidity, 99 Per Cent (About)			Humidity, 77 Per Cent (About)		
Fiber No.	*R*		*R* *		
	Cotton	Silk (Tussah)	Group No.*	Cotton	Silk †
1	2600	3300	1	563,000	
2	4700	4500	2	736,000	
3	3800	5140	3	680,000	
4	5600	4740	4	822,000	
5	3000	6650	5	625,000	
6	4600		6	577,000	
7	6000		7	822,000	
8	4500		8	733,000	
9	5500		9	736,000	
10	6000		10	830,000	
11	4000		11	653,000	
12	4000		12	824,000	
			13	760,000	
			14	867,000	
			15	725,000	
			16	938,000	
			17	820,000	
			18	682,000	

* Each group consisted of 60 single fibers attached to the electrodes so that they were in parallel. R^* is the average resistance per single fiber calculated from that of 60 in parallel. The experimental technique is described elsewhere.[3a]

† The values of R^* for silk at this humidity were found to be of the order of several million megohms, i.e., beyond the limit of accurate measurement with equipment available at the time the study of single fibers was under way.

which, considering the nature of the material, is surprisingly uniform for different fibers taken from the same material. Similarly, Table I*B* shows that threads [9] of cotton and silk also have a uniform resistance; this suggests that the interfiber contacts do not have a large effect on the resistance of the thread as a whole. Table I*C* shows the resistance of the servings on wires; the resistances are for short twisted pairs (2 in. long). This shows also that even where the voltage is applied transversely to the long axis of the fibers—which would tend to make contact resistances more important than when the voltage is applied parallel to the long axis—the resistance of different samples of the same material is fairly uniform. These facts suggest that inter-

[9] Because of their uniformity, small samples of thread (½ in. lengths) have been used in this laboratory as a convenient means of comparing the insulating quality of cottons and other textiles.

TABLE I*B*

Resistance of Cotton and Silk Threads

Length ½ in. Temperature 25 deg. cent.

Sample	Resistance Megohms Cotton Humidity 77%	Silk (Spun) Humidity 90%
1	4160	21,100
2	4220	22,700
3	4100	28,000
4	3730	14,500
5	4020	30,600
6	3820	
7	3900	
8	3715	
9	4050	
10	4100	
	Aver. 3982	23,380

TABLE I*C*

Resistance between Twisted Pairs of Cotton and Silk Insulated Wires

Humidity 77 per cent Temperature 25 deg. cent.

Sample	Resistance Megohms Cotton	Silk (Tussah)
1	5.45	2200
2	3.96	1890
3	5.20	1685
4	3.96	1685
5	3.50	2250
6	4.05	1970
7	5.60	
8	5.15	
9	4.37	
10	4.76	
11	4.00	
12	4.37	
	Aver. 4.53	1942

fiber contact resistances are only secondary or negligible in determining the resistance of a thread or other mass of fibers. Further evidence of this is given by the data in Table II, which show that even when the length of a thread considerably exceeds the length of a single cotton fiber, the resistance is approximately proportional to the length; if interfiber resistances were large, the resistance per unit length would increase considerably with the length of the thread measured.

The above results also suggest that electrical conduction takes place primarily through moisture in the interior of the fibers rather

than through moisture condensed on their surfaces. Other evidences that this is the case may be found in the relationships of conductivity to humidity, moisture content and electrolyte content, as well as the absence of any obvious relationship between the physical dimensions of different classes of fibers and their electrical behavior.

TABLE II

RESISTANCE OF DIFFERENT LENGTHS OF COTTON THREAD

Humidity about 77 per cent Room temperature

Length Inches	Resistance Megohms Total	Per Inch
0.5	21,700	43,400
1	41,750	41,750
3	153,000	51,000

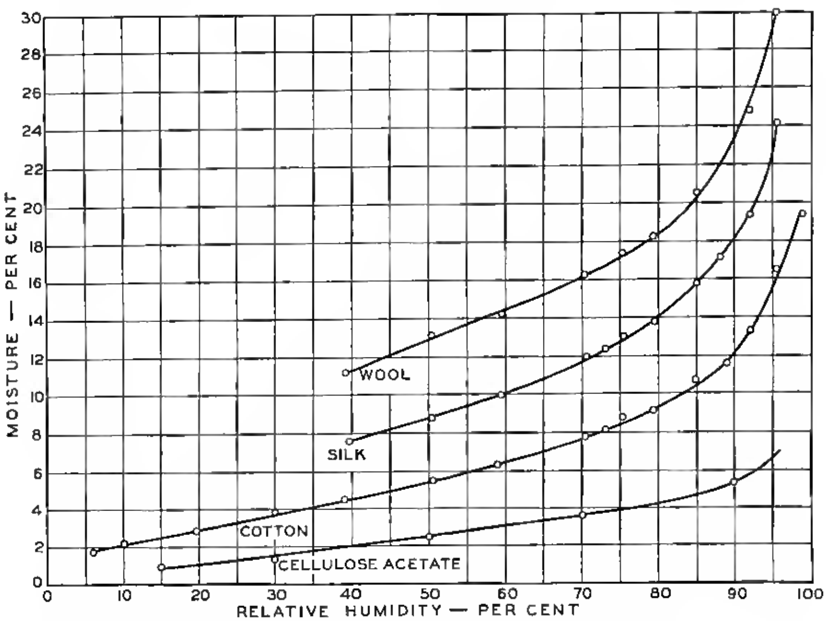

Fig. 1—Dependence of moisture content of textiles upon relative humidity of atmosphere with which they are equilibrated

While the form of the sample is not of predominating importance with reference to the insulation resistance of either cotton or silk, the marked contrast except at very high humidity between cotton and silk in all forms of samples should be noted. Both these facts and other available data justify the inference that the dielectric properties of textiles are determined primarily by the composition or

internal structure of the fibers, not by the twist of threads or the lay of servings.

The moisture content of each sort of textile depends directly on the humidity of the atmosphere. Fig. 1 shows the best data available for the moisture content of silk, wool, cotton, and cellulose acetate in equilibrium with air over considerable ranges of relative humidity.

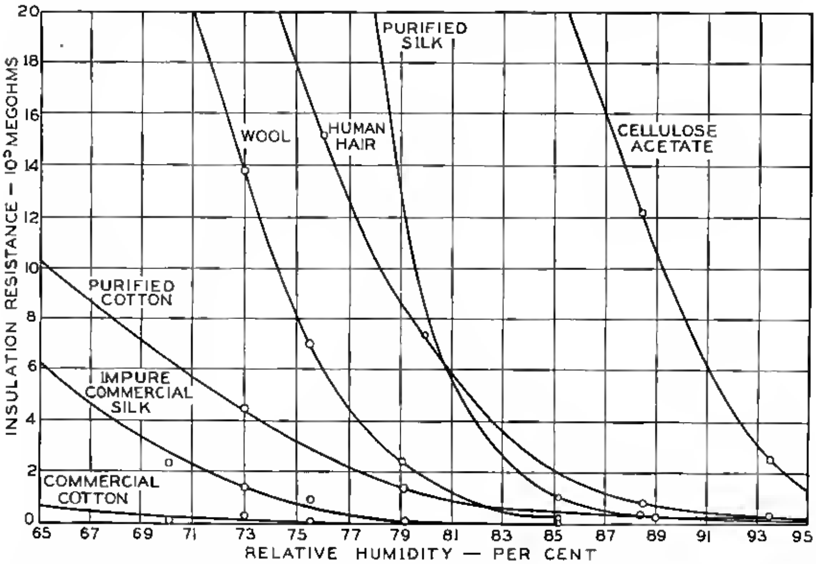

Fig. 2—Insulation resistance of ½ inch lengths of textile threads as affected by relative humidity of atmosphere. The purified cotton and purified silk had been submitted to a washing procedure to remove electrolytes. The impure silk was a commercial specimen representing somewhat more than usual contamination with electrolytes, while the commercial cotton is representative of its class.

The data for silk and wool were taken from a paper by Schloessing; [10] those for cotton are due to Urquhart and Williams; [11] while those for cellulose acetate represent the figures of Wilson and Fuwa,[12] who also give corresponding data for several textiles and many other substances. It is sufficient for our present purpose to emphasize the orderly dependence of moisture content upon the relative humidity of the atmosphere without discussing secondary phenomena or the full significance of the curves.

The relation of electrical behavior of each textile to relative humidity is also very close. Fig. 2 shows the insulation resistance of each of

[10] Schloessing, Th., *Bul. Soc. Encour. Indust. Nat. 8*, 717 (1893); C. R. *116*, 808, 1893. Text. World Record, Boston, Nov. 1908, p. 219.

[11] Urquhart and Williams, *J. Textile Inst. 15*, 143 (1924).

[12] Wilson, R. E. and Fuwa, Tyler, *Ind. & Eng. Chem. 14*, 913 (1922).

the above fibers plotted against relative humidity over the upper part of the range of atmospheric humidities. It is not practicable to plot the resistance over the entire range of humidity directly in this way, on account of the wide range of insulation resistance values which are obtained. In order to depict the fact that there is a consistent relationship throughout the range, we have plotted in Fig. 3

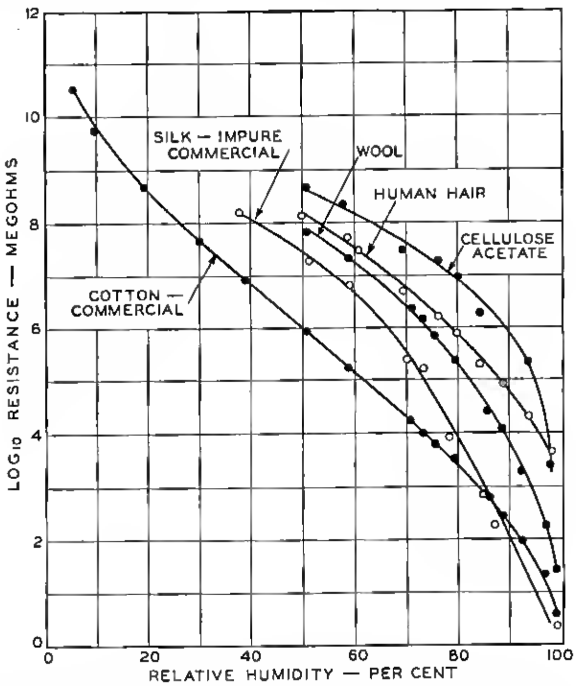

Fig. 3—Log insulation resistance of ½ inch lengths of textile threads *vs.* relative humidity of the atmosphere. For description of samples see Fig. 2. For tabulated data see reference 3*a*

Log Insulation Resistance *vs.* Relative Humidity as far as values are at present available. When considered together, these three charts show that the insulation resistance of a textile depends on its moisture content, which in turn is a function of relative humidity. In the series of papers previously mentioned,[3] the electrical behavior of textiles in relation to relative humidity and moisture content is discussed more fully.

Aside from the common property of dependence of electrical characteristics of textiles upon their moisture contents, several other phenomena of electrical behavior have been encountered which are

common to all. If any textile within our experience, including cellulose acetate (or even glass), be brought in contact with two electrodes of opposite polarity in the presence of atmospheric moisture, the electrical properties of the material undergo a change with a rapidity dependent on the current and in turn upon the voltage, the length of path, and the humidity. Such a change in the properties of insulating materials with continued application of voltage has been discussed recently by Granier, who advanced the explanation [13] that it is due to the presence of electrolytic impurities in the materials. However, the great magnitude of this change, which may occur in textiles when freely exposed to ordinary atmospheres, seems to have been very little appreciated.

TABLE III

RATE OF CHANGE OF RESISTANCE WITH TIME OF APPLICATION OF VOLTAGE FOR SOME FIBROUS MATERIALS

Separation of Electrodes ½ in. Humidity 97 per cent (approx.) Voltage 275

Cotton		Silk		Cellulose Acetate Silk		Paper	
Time Secs.	Resist. Megohms	Time Secs.	Resist. Megohms	Time Secs.	Resist. Megohms	Time Secs.	Resist. Megohms
70	19.8	30	8.1	80	9.3×10^3	55	4.54
150	33.6	90	12.8	1250	1.01×10^4	100	8.30
200	40.5	120	19.8	2300	1.06×10^4	200	11.2
300	45.1	153	26.7	3200	1.11×10^4	260	19.8
400	50.0	220	40.5			520	32.2
500	57.5	300	47.8			615	38.5
900	68.2	640	54.8			1000	42.7
1900	82.0	1250	58.4				
3000	91.0	2100	79.5				
4000	99.0	2320	107.0				
		3000	153.0				

In our experiments the insulation resistance rises to a value perhaps 10 to 100 times the original value, depending on the nature and condition of the fiber. A few typical cases are given in Table III. This phenomenon will be referred to as polarization. This rise in resistance appears to be largely due to substantial denudation of some intermediate portion of the fiber of electrolytic impurities, which in general tend to accumulate in the vicinity of the electrodes. The phenomenon involves the possibility of chemical reactions between the products of the electrolysis and the material of the electrodes, as well as the evolution of gases and the conversion of soluble salts into insoluble products. As regards the mineral constituents of

[13] Granier, J., *Soc. français Elec. Bull.*, *3*, 480 (1923).

cotton, it can be observed by ashing the polarized fiber that the ash lies largely in those portions which were adjacent to the electrodes and especially to the cathode. The electrical resistance is very unequally distributed along such a polarized fiber or thread, the positions of maximum resistance depending upon the conditions of polarization.[3c] Interruption of the current after polarization leads to a gradual restoration of the original electrical properties and a redistribution of the ash constituents with a speed depending largely on the humidity. Reversal of polarity is accompanied by a rapid drop in insulation resistance, followed upon continued application of voltage in the reverse direction by polarization in the opposite sense. Interruption of the circuit after polarization leaves large potential differences on the opposite ends of the fiber, which persist for several minutes. The cathode region is found to be alkaline in reaction, the anode region acidic. The polarized fiber is therefore a concentration cell.

The electrolysis of cotton may be carried out experimentally in another way. If cotton yarn is immersed in water in each of a series of cells separated from one another by a parchment paper membrane and a direct current is passed through the cells for some hours, the impurities tend to accumulate near the electrodes, with the development of acidity at the anode and alkalinity at the cathode, as is usual in the electrolysis of a saline solution. If the samples of cotton yarn be now removed and brought into equilibrium with an atmosphere of standard humidity, the insulation resistance is found to vary fairly regularly with the original position of the sample in the series of cells, being greatest in some intermediate cell and diminishing toward either electrode. The precise position of the maximum varies with the nature of impurities present in the system. The highest insulation resistance may be many times that of the original cotton.

Perhaps the most significant evidence of the importance of electrolytic impurities in silk, wool, cotton, and to some extent other textiles, is the fact that their electrical characteristics can be greatly improved by thorough washing with water though without altering qualitatively the general nature of the electroconducting phenomena which characterize them. Fig. 2 illustrates the result of washing upon the insulation resistance of cotton and silk threads. The improvement in insulation resistance of cotton and silk upon washing ranges commonly from fifty to one hundred fold, under any of the commonly prevailing conditions of atmospheric temperature and humidity. This improvement is accompanied by diminution of the ash content, in the case of cotton from about 1.0 per cent to 0.15 or 0.25 per cent. It produces only a slight reduction in the equilibrium moisture content

of the cotton over the ordinary ranges of atmospheric humidity. The sensitivity of the washed cotton to continued application of voltage is much less than that of the original, but polarization still occurs. Commercial silks are similarly affected by washing.

If the mineral contents of cottons which have undergone washing are compared quantitatively with the original contents a decrease is observable, particularly as to potash, but the calcium and magnesium contents are much less altered. Fairly complete removal of potash is apparently essential to good electrical characteristics, but improvement electrically has been attended in some cases by an actual increase in content of alkaline earths. This suggests that interchange of electrolytic impurities between the textile and the water is involved as well as actual removal of electrolytes by the water. Thus in general hard natural waters, i.e., those containing calcium and magnesium salts, have proved as good or better than soft waters when used in economically small amounts. Very exhaustive extraction with distilled water gives excellent results, though not vastly superior to washing with very dilute solutions of alkaline earth salts. Sufficiently complete and accurate analyses of samples of textiles brought into equilibrium with washing liquids and of the kind and quantity of electrolytes in the corresponding liquids have yet to be made to determine the precise importance of the composition of the saline residues. Non-saline electrolytes have also to be considered. This matter requires extended study and the experimental data are reserved for future publication.

The commercial value of such treatments of insulating yarns has proved to be very substantial. The utilization of the products forms the subject matter of another paper[14] from the Bell Telephone Laboratories.

Another common property of textiles is known as the Evershed effect. Evershed [15] found in various insulating materials, including textiles, that insulation resistance does not obey Ohm's law but is less if a larger measuring voltage is used. Evershed's finding as to cotton has been verified by us. This result is easily obtainable if conditions are maintained so that little polarization occurs. But if extensive polarization is allowed to take place the reverse effect is observed and the ultimate resistance is higher in proportion to the voltage used. The conditions which favor polarization are, of course, considerable voltages, prolonged application, high relative humidities, and short paths through the insulation. Evershed's work apparently

[14] Glenn, H. H., and Wood, E. B., This Journal.
[15] Evershed, S., *Inst. Elec. Eng. Jl.* *52*, 51 (1914).

did not involve any special attention to the time of application of voltage.

Evershed's explanation of decreased insulation resistance with increased voltage involves the assumption that much of the water contained in insulations is originally in the form of isolated pools and therefore of no conductive effect at the instant of application of voltage. In support of his theory of "dormant" water, he lays great stress upon his observation that the volume of water present in the insulating materials is far in excess of that which would be required to furnish the observed conductivity if the water were in the form of continuous filaments of uniform cross section. This argument seems impressive and conforms to our own ideas of the distribution of water in textiles. However, according to Evershed, this pool water is electrokinetically spread out into conducting films under electric stress, thus accounting for decreased resistance with increased voltage. A tendency to such movement of water cannot be denied. But it is difficult to harmonize Evershed's conception of electroendosmotic movement of water as the predominating phenomenon with all the facts regarding textiles with which we have had experience; for example, with the fact that the Evershed effect is greatest when the electrolyte content of the textile is high. Electroendosmose in systems designed for its ready detection usually diminishes with increasing electrolyte content except when the concentrations are very small.[16] Further a decrease of resistance with increase of voltage has been noted in other systems in which electrolysis is unquestionably involved and in which electrokinetic redistribution of water seems improbable.

Though sufficient support for an alternative cannot be furnished at present, electrokinesis does not constitute the sole possible explanation of the Evershed effect. The analogy between the moist fiber and an electrolytic cell conforms to a number of other corollary facts about the Evershed effect which are discussed in a more specialized paper by one of the authors.[3c] The various properties which have been discussed are in agreement with the view that the cardinal principle of conduction in textiles is the electrolysis of aqueous solutions.

Distinctive Characteristics of Each Fiber Species

The several kinds of fibers exhibit a number of curious contrasts in the relation of electrical behavior to hygroscopic properties, some of which at first glance appear contradictory. For convenience in dis-

[16] Powis, Frank, *Zeit. Physik. Chem. 89*, 91, 1914 and Burton, E. F., *Coll. Symp.*, Monograph IV, 132, 1926.

cussion, let us classify the commercial fibers into two main groups: (1) the animal fibers, and (2) the vegetable fibers, and a subgroup (2a), the cellulose ester fibers of which the so-called cellulose acetate silk is the sole representative of commercial importance at present. It will be seen by reference to Fig. 1 that over the entire range of relative humidity the animal fibers, silk and wool, absorb more water

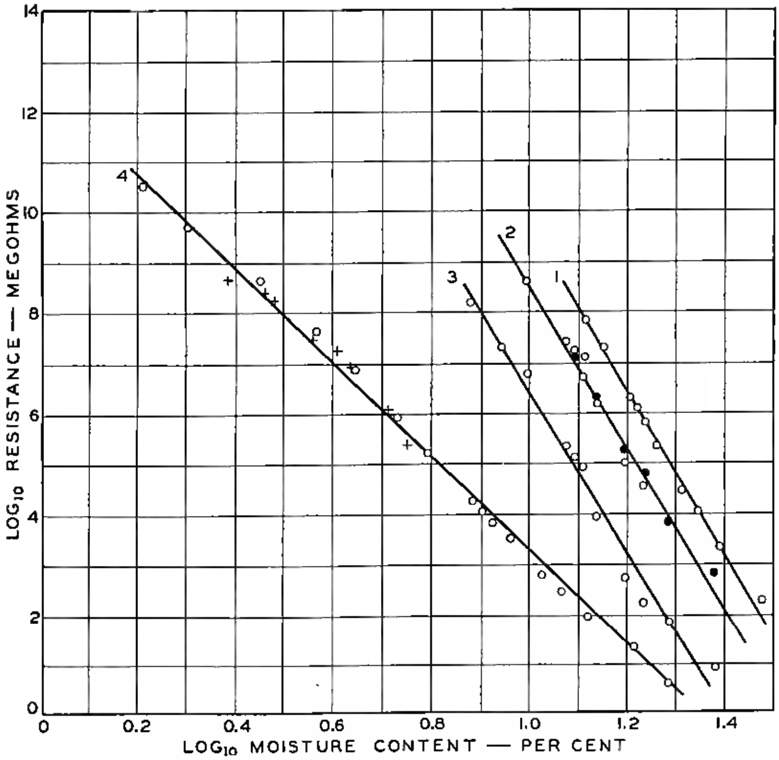

Fig. 4—Insulation resistance as a function of moisture content of textiles
1. Wool yarn
2. Silk threads purified [sample 1 (o); sample 2 (●)]
3. Silk threads impure
4. Cotton threads (o); cellulose acetate threads (+)

than the natural vegetable fibers. This is true whether we deal with fibers in their natural impure state or after a washing process which has been shown to improve greatly the electrical characteristics of both types of natural fibers. Cellulose acetate absorbs less water at any given humidity than either class of natural materials.

We have seen that for any given kind of fiber there is an orderly dependence of electrical properties upon the moisture content of the

fiber and in turn upon the relative humidity of the atmosphere. The more water present in any given fiber, the poorer are the electrical properties. If the amount of water in fibers were the sole determinant of electrical characteristics we would expect the animal fibers to be, at a given humidity, the poorer electrically of the classes enumerated above. But this is emphatically not the case. With respect to electrical properties, we find that the vegetable fibers are inferior to the more hygroscopic animal fibers and are also inferior to the least hygroscopic variety of commercial fiber, viz., cellulose acetate. To make the existing contrast clear we have plotted in Fig. 4 for the several textiles, Log Insulation Resistance *vs.* Log Moisture Content. When so plotted the values for each kind of fiber fall approximately on straight lines throughout the range of actual measurement. The relative position of the curves for animal fibers to the right and above that for cotton [17] means that the animal fibers have the better insulating qualities in spite of higher hygroscopicity.

The slopes of these lines have an even greater significance for they indicate the relative sensitivity of the fibers to an increment of moisture. Since the slope for the animal fibers is greater, it is evident that the animal fibers are more sensitive electrically to moisture than cotton. Under a given set of conditions they are not only wetter than cotton, but are more sensitive to the effects of further increments of moisture and yet they have a higher insulation resistance.

In one respect alone can we say that cotton is preferable as an insulating material. It has the merit of being more nearly uniform in behavior under a variety of weather conditions. When the amount of moisture taken up from the surrounding atmosphere by silk or wool is doubled, the electrical leakage increases by a factor of 50,000 to 100,000, while that for cotton rises by a factor of only 600.

The position and slope of the values for cellulose acetate are of great interest as the curve coincides with that for cotton, indicating that moisture affects these two fibers in a very similar manner. The essential electrical difference between these two appears to be satisfactorily accounted for by the fact that cellulose acetate absorbs less water than cotton at any given relative humidity of the atmosphere. The conversion of cotton which is essentially cellulose into cellulose acetate by the process of acetylation, has, as could be predicted on chemical grounds, reduced its hygroscopicity but apparently has not modified its structure greatly. Cellulose acetate is therefore put in a subgroup rather than in an independent classification.

[17] The threads referred to are approximately, but not precisely, of the same size. This variable is by no means sufficient to account for the higher position of the animal fibers as compared with cotton.

The reader will have been led to ask several questions. Why do the several kinds of fibers differ so much in absorption of water and particularly why does not a given amount of water affect them all alike electrically? He will want to know if the mere fact of animal, vegetable, or artificial origin is associated with a particular type of electrical or hygroscopic behavior. He will wonder whether there is any fundamental resemblance between the silk which is rapidly extruded by a worm and the hair which grows so slowly on a sheep's back. He will inquire whether there is sufficient justification for classifying other vegetable fibers with cotton. To these questions only partial and to some extent speculative answers can be given.

We are justified on chemical grounds in classifying the fibers in the same way which we have found to be convenient for discussion of their hygroscopic and electrical properties. How much importance should be attached to this correspondence between the chemical and electrical classifications cannot be determined at present. However, the correspondence seems suggestive and deserving of a brief discussion. The first class, that of animal fibers, has a common chemical nature in that they consist largely of proteins. Proteins are molecular aggregates of colloidal size composed in turn of simpler substances known as amino acids. Each of the constituent amino acids contains both an acidic and a basic group, so that in acid solutions they behave as bases and in alkaline solutions they behave as acids. This so-called amphoteric property is due to the presence of an acidic oxygen nucleus and a basic nitrogen atom, which are almost invariably adjacent to one another. Amphoteric properties persist in the proteins which are formed by union of many amino acids in a single molecule. This is illustrated by the fact that either amino acids or proteins in a solution which is subjected to a d.c. voltage tend to migrate to positions intermediate between the electrodes where the acidity is such that they are equally ionized as bases and as acids. The combination of adjacent acidic and basic groups within a single molecule gives them a salt-like property which may be significant. It is reasonable to associate the hygroscopic quality of the proteins with these groups as the molecules are usually without groups of polar character other than the paired groups mentioned.

That their common protein character is responsible in some way for the properties of principal interest from the insulating standpoint is rendered the more probable by the close resemblance of silk and wool, as shown by the approximate parallelism of their curves in Fig. 4. This resemblance is shared in considerable measure by other hairs than wool.

The second class of fibers, coming from the vegetable world, are alike in being composed of cellulose, a substance like the protein in having a high molecular weight but unlike it in that its polar groups are hydroxyls which have a faintly acidic rather than amphoteric nature. These are the groups in cellulose with which water is likely to associate itself. Such data as are available concerning vegetable fibers other than cotton, notably linen, ramie, manila hemp, and wood pulp, indicate a strong resemblance not only chemically but hygroscopically and electrically.

The subclass embracing only cellulose acetate as a commercial fiber is chemically more neutral and non-polar in type than other cellulose fibers, with which fact it is reasonable to associate its lower hygroscopicity and consequent better electrical characteristics. It is probable that cellulose nitrate and cellulose ethers will be found to fall in this class but artificial silks other than cellulose acetate absorb more water and appear on chemical grounds to be better classified with the cellulose fibers of natural vegetable origin.

It cannot be decided from available information whether the similarities and differences in electrical properties among the textiles are traceable directly to chemical similarities and differences or indirectly to physical (colloidal) structures which in turn are determined by chemical composition. In either case it is possible to account for the high sensitivity of all the fibers to moisture and the variation in sensitivity from species to species by assumptions as to the distribution of water in them. Water which collects in any isolated form in the material will have little electrical effect compared with that which forms continuous filaments. The distinction we are making is essentially the same as that of Evershed when he referred to part of the water as "dormant," though we do not attach the same importance as he does to electrokinetic redistribution of water under electric stress. Each increment of water may be considered as undergoing partition into two portions, one causing a large increase of conductivity and one having a negligible effect, in a ratio determined in some fashion by the structure or nature of the material and the humidity of the atmosphere. The ratio of the two portions which are in equilibrium via the surrounding atmosphere will be subject to constant readjustment under changing conditions.

The fact that the electrical characteristics of the two classes of fibers as affected by moisture appear to be specific properties of the substances involved suggests some highly regular distribution pattern of conducting water paths determined by the chemical or physical (colloidal) structure of the material. Such a regular pattern may

involve only water condensed upon the surfaces of the elements of structure in such a way that the thickness of the film varies regularly from point to point through the material. Accumulation of water at thick points would have little electrical effect, while that in thin portions would be very significant. An alternative regular mode of distribution would involve water in part dispersed in solution or chemical combination within the units of structure of the material and in part in fairly uniform thin films on their surfaces, in which case the latter would have the major electrical consequence. While such a regular form of distribution seems preferable, it is perhaps not the only way of accounting for the electrical properties observed.

The curves as shown in Fig. 4 for both cotton and silk are straight lines within the experimental error but the assumption is not justified that they can be projected as straight lines to zero humidity. At the lower ranges of humidity the resistance of silk is so high as to exceed the limits of our present technique of measurement. Over some range below 40 per cent relative humidity, it may well be that the sensitivity of the animal fibers to increments of moisture is less than that of the cellulose fibers. If so, the break in the curve would have great interest in connection with determining the mode of water distribution and in turn the colloidal structure of the materials in question. It is hoped that an extension of the study in this direction will be possible in the future.

Summary

Attention is called to the practical importance of water in all insulators and especially to the extreme electrical sensitivity to moisture of textiles as a class.

Significant amounts of electrolytic impurities occur in many insulators.

In textiles in the presence of moisture such impurities are responsible for very conspicuous features of electrical behavior. Data are given showing their effect on the insulation resistance of cotton and silk.

The insulation resistance of textile fibers in moist air rises greatly with duration of d.c. voltage, accompanied by many evidences of electrolysis of aqueous solutions of impurities in the textile.

The instantaneous insulation resistance of fibers decreases with increase of the measuring voltage as previously shown by Evershed. However, this fact does not necessarily support his idea of kinetic redistribution of water in textiles, as this behavior is also compatible with the nature of electrolytic conduction.

Electrolytic impurities may be washed out of textiles and sub-

stantial practical improvements effected thereby. The increase of resistance is of the order of 50 times.

Fibers are classified according to their electrical behavior in a manner which is also in harmony with their chemistry as follows:

(*1*) *Animal fibers.*

These are of protein nature and are characterized by high moisture content at ordinary humidities and by great electrical sensitivity to further increments of moisture, yet possess excellent insulating properties under usual atmospheric conditions.

(*2*) *Vegetable fibers.*

These are of cellulosic nature and are characterized by lesser moisture absorption and lesser electrical sensitivity to further increments of moisture, yet possess relatively poor insulating properties over the range of prevalent atmospheric conditions.

(*2a*) *Cellulose acetate.*

This absorbs little water and accordingly has excellent insulating properties under like conditions.

The differences in electrical behavior of the two main classes of textiles are believed to be due to differences in the space patterns according to which water is distributed within the individual fibers. The patterns are probably determined directly or indirectly by the chemical composition of the fibers and associated with the colloidal structure.

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